The use of Virtual Prototyping to rehearse the sequence of construction work involving mobile cranes

Abstract:

Purpose
Rehearsing practical site operations is without doubt one of the most effective methods for minimising planning mistakes because of the learning that takes place during the rehearsal activity. However, real rehearsal is not a practical solution for on-site construction activities as it not only involves a considerable amount of cost but can also have adverse environmental implications. One approach to overcoming this is by the use of virtual rehearsals.

Design / methodology / approach
The paper describes a system involving two technologies, Virtual Prototyping and 4D, to assist construction planners in testing the sequence of construction activities when mobile cranes are involved. The system consists of five modules, comprising input, database, equipment, process and output, and is capable of detecting potential collisions. A real-world trial is described in which the system was tested and validated.

Findings
Feedback from the planners involved in the trial indicated that they found the system to be useful in its present form and that they would welcome its further development into a fully automated platform for validating construction sequencing decisions.

Research limitations / implications
The tool has the potential to provide a cost effective means of improving construction planning. However, it is limited at present to the specific case under consideration, namely that of crane movement.

Keywords: Construction planning, Sequencing, Mobile crane, Virtual Prototyping

Research Type: Research paper

Introduction

Mission rehearsal ideas, such as Virtual Prototyping (VP), exist in many areas of human endeavour, including education (e.g. Hill *et al*., 2003), medicine (e.g. Cates *et al*., 2007), fire fighting (e.g. Tate *et al*., 1997), underwater exploration (e.g. Davis and Brutzman, 2005), military (e.g. Rickel *et al*., 2002) and psychology (e.g. Marsella and Gratch, 2001), and have been common in the manufacturing industry for a long time (Aust and Dunlap, 2002). However, such ideas have received little attention to date in the construction industry. The main reasons for this appear to be that 1) developing the prototype of a building involves a substantial amount of monetary and human resources, 2) each construction project is unique in terms of its location, constraints and requirements, and 3) the limited amount of construction time available for rehearsals. The critical path method (CPM) and bar charts are still widely employed by project teams as the main tools for producing project schedules and coordinating the activities of those involved (Koo and Fischer, 2000). At present, most construction planners in Hong Kong use commercial management software, such as Primavera Project Planner (P3) or Microsoft project, which are all based on heuristic methods for planning and control schedules.

Previous research into the use of VP includes simulating the construction plan and schedule as an alternative to CPM to achieve the degree of co-ordination, understanding and optimisation needed (Li *et al*., 2009). In the case of material-handling equipment such as cranes, however, there is a lack of consideration of the important detailed operations and space requirements needed for the equipments' motion. Existing structures, such as electrical power lines and building structures, can come into spatial conflict with crane operations (Akinci *et al*., 2003; Guo, 2002). There are also many uncertainties involved.

The crane is the one of the most critical components in the construction plan and schedule, as it is linked with many associated activities relating to lifting and hoisting. For the past two decades, schematic models (Huang and Halpin, 1994) and the iconic animation of schematic models (Zhang *et al*., 2002) have been widely used to improve the conceptual understanding of modelled systems. These methods, however, neither provide detailed solutions nor reflect the workspace requirements and/or limitations of the crane operations themselves.

The aim of the research reported in this paper was to investigate an approach to simulating the motion of cranes to test the feasibility of associated construction sequencing and generate construction schedules for review and visualisation. The paper first describes related research regarding VP, four-dimensional (4D) technology and collision detection in a simulated crane environment. A VP model is presented together with a four dimensional (VP+4D) system consisting of five modules: 1) Input Module, 2) Database Module, 3) Equipment Module, 4) Process Module and 5) Output Module. A real-world trial is then presented to test and validate the system in its ability to generate construction schedules. Further improvements to the VP+4D system are identified and discussed in the final section.

Related research

Virtual construction visualisation is suitable for conducting rehearsals of the construction process for construction planners to review and identify potential spatial conflicts. As Kamat and Martinez (2003) have recognised, the project and operations provide two levels of detail at which visualisation and models of construction processes are formed. At the *project level*, construction progress is visualised as a set of building components being constructed over a period of time. At the *operations level*, the dynamic motion of resources (e.g., crews, pieces of equipment, and materials) used during operations are visualised.

At the project level, the common tool for visualisation of the construction schedule is 4D, which is a three dimensional (3D) model combined with a time/schedule, to enable planners to visualise the construction sequences involved. Adjei-Kumi and Retik (1997) have applied the concept of Virtual Reality to visualise construction plans using a library-based 4D model. Similarly, McKinney and Fischer (1998) developed 4D tools for generating, evaluating and visualising construction schedules with CAD, while Koo and Fischer (2000) adopted 4D CAD in commercial building construction in order to minimise the limitations of the traditional CPM and bar chart analysis. Dawood *et al*. (2003) have also developed an integrated database to act as an information resource base for 4D/VR construction process simulation and evaluation through building projects. Likewise, Wang *et a*l. (2004) developed a 4D Management for Construction Planning and Resource Utilization system (4D-MCPRU), which links a 3D geometrical model with resources to obtain the necessary resource requirements. In addition, Russell *et al.* (2009) used linear scheduling and 4D CAD to visualise high-rise building construction. Sampaio and Santos (2011) used a virtual reality connected construction schedule to allow the visualisation of different stages of construction. There is no doubt that the main and direct benefit is that visualisation can help to improve understanding of the construction schedule and the communication between clients or colleagues. However, it cannot provide the analysis or optimisation of plans.

Another important use of 4D is to analyse spatial conflicts. Akinci and Fischer (1998), for example, used a 4D model to perform and analyse time–space conflicts, while Akinci *et al*. (2002) developed their 4D WorkPlanner Space Generator (4D Space-Gen) to generate project-specific work spaces from a generic work space ontology and a project-specific IFC (industry foundation class) based 4D model. Dawood and Mallasi (2006) also used 4D visualisation for resolving conflicts between work-face construction activities, and Tantisevi and Akinci (2009) presented an approach to automatically simulate the motion of mobile cranes for collision detection, with a recent contribution from Lai and Kang (2009) involving the development of a collision detection algorithm for virtual construction simulation. Space is one of the elements of 4D, and so 4D can provide the application for analysing activity conflicts. However, the above research focused only on either the project level or the operations level.

At the operations level, Discrete Event Simulation systems have been used to improve productivity by minimising mistakes. Examples include CYCLONE (Halpin, 1977), UMCYCLONE (Ioannou, 1990), CIPROS (Tommelein *et al.,* 1994), and DISCO (Huang and Halpin, 1995). Kamat and Martinez (2003) also used discrete-event simulation to develop an approach (VITASCOPE) for generating a 3D animation of equipment operations based on a sequence of geometric transformations.

Finally, it is significant to note that a considerable amount of research has been specifically aimed at modelling crane operations in order to identify related spatial conflicts. Sivakumar *et al.* (2003), for example, developed a computer aided path planner for two cranes during material-lifting operations based on a robot path planning algorithm. Tantisevi and Akinci (2007), on the other hand, presented an approach for generating workspaces and identifying spatial conflicts for moving mobile cranes. Kang *et al.* (2009) also developed a physics-based simulation and animation of crane motion for the erection of steel and precast reinforced concrete buildings to minimise construction time and collisions. In addition, Kamat and Martinez (2001) developed a general-purpose 3D visualisation system that enables spatially and chronologically accurate 3D visualisation of modelled construction operations. Moreover, Kamat and Martinez (2007) developed a system to identify and report such collisions at the operational level in relation to construction resources, including machinery, in 3D animations of construction operations, while Al-Hussein *et al.* (2006) proposed the integration of 3D visualisation and simulation for tower crane operations. However, the construction master programme has not been considered. To have an accurate rehearsal of construction operations, the simulation should reflect project level processes in the same way as 4D. Tantisevi and Akinci (2009) presented an approach to generate crane operations based on project-level process information for identifying possible spatial conflicts. However, the research did not utilise the operation of the mobile crane to estimate the lifting time, and failed to use the capabilities of the 4D model to create a detailed construction schedule. In summary, little research has combined both project and operation levels in order to improve construction planning. For real projects, it is necessary to consider both these levels together in order to comprehensively rehearse the planning involved.

Sequencing rehearsal using a combination of VP and 4D

Virtual Reality (VR) is one of the techniques that can be used to represent detailed activities at the operational level. VR is a computer simulation of a system, either real or metaphorical, that allows a user to perform operations on a simulated system and obtain the effects in real time (Morris, 1992). VP combines the use of VR, motion simulation and other computer technologies to create digital prototypes.

The VP process comprises the construction and testing of a virtual prototype, or digital mock-up, that is a realistic computer simulation of a physical product's life-cycle and which can be analysed and tested (Dai and Göbel 1994; Wang 2002). The simulation also addresses broad issues of physical layout, operational concepts, functional specification and dynamic analyses for a range of operating environments (Xiang *et al.,* 2004; Drews and Weyrich, 1997).

VP's power function is motion simulation, in which machinery can be modelled and analysed. This involves accurately mimicking the movement of machinery joints. One type of machinery motion analysis is that of kinematics performance (such as velocity, acceleration, position, displacement and rotation), for verifying the correct geometry of motion as intended by the design, and then identifying possible interferences and collisions between various parts of the assembly (Zorriassatine *et al.,* 2003). Instead of building expensive physical prototypes, motion simulation can also be used during tolerance analysis so as to provide integration and enable space requirement tests.

In this study, the motion model (crane) consists of 3D models and constraints. The 3D models are drawn by CAD, which represents the parts or assemblies involved. The constraints include 1) the entities between parts or assemblies, such as revolution and slot joints, that limit the degrees of freedom of movement of the associated parts or assemblies, and 2) their capacities, such as velocity, turning ratios and lifting times. Also, VP provides a platform for a design modulus system to integrate Building

Information Models (BIM), machinery, information and construction planning in order to validate the associated construction sequences.

4D modelling is simply 3D plus time. For this research, time represents construction sequence, which is the sequence of the installation of the construction elements. VP is an effective tool for avoiding collisions caused by the dynamic motion of resources at the operation level while also being useful in simulating a variety of construction methods or schedules at the project level in relation to the construction of the building components over time (Li *et al.,* 2009). As the project and operation levels place different elements in different perspectives, a more comprehensive approach to effectively analysing the feasibility of construction plans is to take both into consideration simultaneously. To do this, it is necessary to link the VP technology with 4D technology so as to visualise construction schedules in 2D, 3D and 4D environments.

Importance of the research

Architectural designs of buildings are becoming more complicated, significant and unique, with structural designs also being much more complex than hitherto. For construction planners and engineers, each new project is a challenge as it is different from previous ones. As structural designs are not standardised, construction problems arise due to the unique size and length of each structural member.

As most steel members have unique sizes and lengths, a critical issue when installing structural members is that the identified members should be in the designated locations. Generally, this would not be difficult. If numbers are assigned to all structural members and marked on them before construction, workers have only to correctly select the numbered members according to the construction framing plan. However, as steel structures are usually complex and large, many members of different types and sizes are involved, which increases the risk of errors. On the other hand, space on construction sites is usually limited, with insufficient room for storing all the structural members needed for the project. Planners therefore need to think of two solutions:

1. Steel members are placed from one level to another until the safety limit is met. For instance, if a structural member is to be taken from the base of a pile, how should the action be performed? Of course, all the structural members above the desired member should be taken away but this is impossible in practice as it is too time-consuming.
2. Only a few steel members are stored on the construction site, for immediate use in the construction process. The remaining steel members are stored on another site or in a factory, creating the need for the frequent transportation of steel members from the factory or storage area to the construction site. However, this raises the question of which of the steel members to transport first and how the schedule should be defined.

A construction schedule for all structural members, indicating the construction sequence (i.e. which members are the first or second to be delivered) provides the solution. In addition, a feasible schedule for all steel members can reduce the time wasted in identifying the structural members needed or waiting to arrive. However, how is the construction schedule designed? It is risky to rely solely on the planner' experience in the absence of any systems to evaluate feasibility and therefore the estimated construction duration is not reliable.

In planning the sequence of steel installation, machinery-moving routes and workspaces are key factors in determining construction duration and need to be taken into account when planning the work. However, although a computerised method such 4D is helpful in demonstrating the sequences involved for all affected parties, it cannot accurately mimic machinery motion and fails to take the machinery's workable area into account.

Research Methodology

A method of rehearsing is presented to minimise planning mistakes in sequencing work involving mobile cranes. The method was developed by first reviewing the literature relating to virtual construction, which identified VP as an appropriate tool to use. Then, once the VP tool for rehearsing the sequencing of work had been developed, it was tested and validated by means of a trial designed to both illustrate the use of the tool and to reveal the practical consequences likely to occur in the event of full implementation in the future.

VP+4D system prototype

For the development of the VP+4D system prototype, the use of structured systems analysis and design method (SSADM) is appropriate as VP+4D follows a SSADM type of methodology that attempts to verify the system design and model the system requirements. Compared with other approaches such as storyboarding and traditional prototyping, the result can lack purpose and the user requirements can be verified or modelled (Mills and Noyes, 1999). The followings procedures are involved in SSADM:

1) *Feasibility study*. The literature review indicated that only a limited amount of research has been done to date on combining project and operation levels. However, such a combination is very helpful for planners in gaining a comprehensive understanding of the situation. From a technological viewpoint, combining VP and 4D should achieve what is needed.
2) *Requirements analysis*. The research aim was to develop a tool for planners to analyse the feasibility of different construction sequences, which should provide enough working space for the crane's operation. In addition, simulating the motion and productivity of the activity enables the planners to estimate the total duration.
3) *Requirements specification*. The requirements to be considered are:
    - motion simulation, for checking the working space
    - motion simulation and productivity of the activity, for estimating duration
4) *Logical system specification*. The structure of the VP+4D system is shown in Figure 1, which comprises five modules:
    - *Input Module,* used for importing the sequence of installation of each structural member, providing a 3D model of the member and determining the location of the storage area.
    - *Database Module*, comprising a means of storing and providing data relating to the productivity rates of construction activities for the Process Module

- *Equipment Module*, used for storing and providing the specifications of the equipment for the Process Module
- *Process Module*, for simulating the final-design output and
- *Output Module*, for producing the results from the Process Module.

5) *Physical design*. The system uses Visual Basic for Applications (VBA), which is an object-oriented programming language to develop specific functions and provides a seamless link between the components of the model. It is supported by a powerful graphical user interface (GUI) in the DELMIA V5 environment and is linked with the Input Module, Database Module and Equipment Module to analyse collision detection during construction simulation. The database of the system is MS Access. 4D software (i.e., Autodesk Navisworks) is used to generate the 4D model.

A detailed description of the each module is provided below.

Input Module

The definition of a construction sequence is the order of installing structural members with an assigned mobile crane. One of the objectives of the research was to test the construction sequence provided by the planners.

The 3D model used involves BIM software to help evaluate performance. The key function of the BIM in the construction field is to allow project planners to view static realistic images and check design errors and collisions (Li *et al*., 2009). In this research, the aim of using BIM was to gain access to the properties and attributes of building components for process simulation. For structural members, these properties and attributes include size, length, type (Column / Beam / Bracing), reference level and designated location.

Determining the location of storage areas is a key factor for the computation of the moving distance of the crane from storage area to lifting position. Using this value, the activity time of the move can be calculated. The area of working and position of the movement boundary is set to prevent the crane moving or working outside its boundary zone. The boundary zone is within the site area and excludes buildings, site facilities and storage areas.

Equipment Module

Mobile cranes are one of the most important equipment resources for steel construction and a 3D model of a crane can be built by any BIM software, with the shape of the model following the specification of the actual crane. The movement specifications of the cranes, such as the range of jib length, angle of elevation of the jib, moving speed, lifting speed, turning speed, moving space requirements and working space requirements, are based on the specifications provided by the machinery manufacturers. This is the library of the equipment model. The models are parametric 3D models and can therefore easily be adjusted by the user.

Database Module

In the Database Module, productivity data for activities, such as welding time, moving and lifting speed of the machinery and preparation time involved in holding the steel in position for welding by workers, are retrieved from the crane specifications and stored in an MS Access database for computation by the Process Module.

Process Module

The VP+4D system uses VBA (which is an object-oriented programming language to develop specific functions and provides a seamless link between the components of the model, supported by a powerful graphical user interface (GUI)) in the DELMIA V5 environment and linked with the Input Module, Database Module and Equipment Module to analyse collision detection during construction simulation. The scheduling data and 3D models from the VP platform are transferred to 4D software (i.e., Autodesk Navisworks) to generate the construction schedule in 4D format.

Mathematical model for estimating the total activity time of mobile cranes

Mathematical models have been developed to estimate the total activity time of mobile cranes. To do this, mobile cranes are treated as robots in order to facilitate the mathematical description and treatment of their motion (Kang *et al.,* 2009). Kang *et al.* (2009) use the Denavit-Hartenberg (DH) notation (Denavit-Hartenberg, 1955) for modelling the motion of a tower crane and a crawler crane, while Kim and Morrison (2011) use same method with derrick cranes for continuous 4D CAD modelling. This research employs the DH notation to model a mobile crane for describing a robot kinematically. This method essentially regards any kind of robot as a set of rigid bodies connected in a chain by joints. For each joint, there is a transformation matrix based on its geometrical relationship. Once the transformation matrix for each joint has been calculated, the total activity time can be estimated.

As shown in Figure 2a, five degrees-of-freedom (DOF) are involved:

1) θ represents the angle of elevation of the crane's jib ,
2) θ_j represents the angle of the rotation of the jib,
3) L_c represents the length of the cable from the end of the jib to the hook,
4) L_{jib} is the length of the jib and
5) θ_h represents the angle of the rotation of the hook.

Mobile cranes are capable of moving freely around their movable area and (x_0, y_0, z_0) represents the 3D position of the crane body with respect to a reference point. The transformation matrix is

$$-$$

$$- \qquad (1)$$

Computation of the workable semi-sphere

The system uses an inverse method to check the working space for lifting structural members. This is based on the proposed sequence of installation of the members. The workable area needs to be computed as the construction sequence is not feasible if the members and the crane clash with the virtual environment (i.e., site boundaries and built structural members) during the simulated installation process.

The model of a typical crane is a simplified version of a real crane, involving the computation of four major parts. The first is the main body and the second is an expandable jib. At the end of the jib is a cable with a hook. Under the hook, there may be a structural element hanging at the bottom of the cable. There are two cases to be considered: hanging a structural column vertically or hanging a structural beam horizontally (Figure 2). These two lifting processes produce different results for the computation of the workable area of the mobile crane despite involving the same size and type of members.

To be accurate, the length of cable from jib to hook needs to be taken into account. In the first case, the workable radius R_c in hanging a structural column is

(2)

where L_{jib} is the length of the crane's jib, θ is the angle of elevation of the jib, L_c is the minimum length of the cable from the end of the jib to the member and L_m is the length of the member. As this is a 3D environment, the working semi-sphere is computed within the working radius (Figure 3).

In the second case, the calculation needs to consider the end of the structural beam. The working radius R_b of the crane when hanging a structural beam is

(3)

where L_{jib} is the length of the jib, θ is the angle of elevation of the jib, L_c is the minimum length of the cable from the end of jib to the member and L_m is the length of the member. A structural beam hanging under the hook may rotate in its available space so the workable space needed may change. A demonstration of Equation (3) is shown in Figure 4. Collision detection is operated within the working semi-sphere to determine if there is enough distance for lifting to avoid collision. The algorithm for collision detection is shown in Figure 5. The system checks the installation of each structural member until a collision is detected.

Output Module

Several results are generated by the Output Module. The first indicates the feasibility of the construction sequence by performing collision checks. If a collision is found, an occurrence time, associated model and snapshot of the collision in the virtual environment is generated. If the result is positive, the construction schedule, a 4D model with a plan view and a construction-scheduling program are generated for visualisation and review.

Trial

The method used to test and validate the system was to visualise and analyse the generated construction schedule and virtual walkthrough for a real-life case-study project. This comprised a steel building, consisting of seven levels, modelled on the sizes and lengths of the associated structural members (e.g., column, beam and bracing and tab). A total of 881 members were involved (Column = 141, Beam = 320, Bracing = 118, Tab = 302). Most of the members had unique sizes and lengths. As the identified members should be in the designated locations, the sequence of installing the structural members should be exactly correct.

The structural members were designed and modelled using AutoCAD 3D initially. However, unlike BIM, AutoCAD lacked a function to embed the information for each model. Each member of the model contains one attribute, a name, which needs to be transferred to the BIM platform, assigned the information for each member and imported into the input module of the 4D+VP system. In this module, the planner defined the locations of the storage and boundary areas in the plan view of the site layout in the system. The text file for the type of construction sequence was also imported. The file displays the steel construction sequences in order.

For the next step (Equipment Module), the planner selected the mobile crane model, which included the physical capacity and moving and working space requirements. The model simulates the work ability into the virtual environment and was built beforehand based on the planner providing the equipment information from the formal equipment specifications.

During the first part of the simulation (Process Module), a mobile crane was selected from the equipment module to compute the workable semi-sphere. Next, the system tested the suitability of the working area of the mobile crane by using the collision detection capability until a collision was detected or all structural members were installed without any collisions. At the same time, the system computed the duration of all activities, such as the time involved in moving from the storing location and lifting location and the lifting time of the mobile crane based on the mathematical models. All the types of activity durations and productivity rates needed are related to steel installation welding times in the database module, and were summed to generate the total duration. Of course, if a collision was detected, no duration could be generated. Finally, the results of testing the construction schedule were generated through the output module.

The planner prepared three sets of construction sequences for testing, the sequence of steel installation being based on his construction knowledge. Three results were generated from the simulations (Table. 1). As shown, test 3 failed - meaning a collision had occurred. The member B20 could not be lifted to its destined location as a collision had occurred between the mobile crane and built structure members (Figure 6). This indicates the member B20 should be built earlier than other members in that area. When a clash occurred, the VP+4D system generated a virtual environment for planners to visualise and walkthrough the clash event. The planner was therefore able to visualise the issue in detail in order to understand the cause of the clash. When a collision was detected, the construction schedule and the total duration were not generated.

The other two test results were positive, indicating that the construction sequence was workable and ensuring that all the activities involved in lifting members at the designated location had enough working space. Also, construction schedules with time in 4D format (Figure 7) were generated for the planners to visualise and review. The construction duration was then estimated based on the productivity data of all the involved activities. The total duration of test 1 and 2 was 120 days and 109 days respectively as test 1 was more smoothly sequenced. Comparatively, test 2 was better planned. The final product in 4D format provided the visualisation platform for the planners to present the best construction sequence to the various other parties involved to improve their understanding and for further discussion.

Discussion

The feedback received from the planners suggested that the 4D+VP system effectively tested the feasibility of construction sequencing of mobile tower cranes. However, this was solely to test the preliminary concept of the sequence and duration of the steel erection work involved. The system is not yet able to test the whole process as construction planning consists of both visible and invisible work, such as temporary work and consent approval. However, it is still sufficient for the preliminary stages of construction, and more accurate and reliable than results based on experience alone.

To validate the accuracy of the collision detection system, the user can visualise the situation in the virtual environment to understand how the mobile crane may clash and with which items. That is, clashes between the lifting member and the existing built members.

Finally, it should be noted that, while the most advanced previous similar work utilises VR to help the planner to rehearse and test the construction process (Waly and Thabet, 2002), it does not utilise the operation of the mobile crane to estimate the lifting time and therefore fails to fully utilise the capabilities of the 4D model. The VP+4D system provides a rehearsal platform for planners to test both sequencing, the effects of collision detection and a 4D model to enable any reviewing and further planning necessary.

Conclusion

The literature review revealed a limited amount of research to date combining the project and operation levels of construction work. The research reported in this paper specifically focused on this in the form of the rehearsal of construction sequencing and a new approach is presented, which simultaneously takes the project and operation levels into consideration in analysing the feasibility of the construction plan. This involves the use of a VP+4D system to assist construction planners test the feasibility of the construction sequences involving mobile cranes. The composition of the system is described, including its five modules and collision detection capabilities. A trial implementation of the system that was conducted for illustration and validation purposes is also recounted.

The results confirm that construction scheduling in a virtual environment in 4D format can provide a platform for planners to review and study the construction processes involved. In addition to providing a vital aid to planners, the approach also has the potential to help provide construction management trainees with a cyber-safe environment in which they can learn through virtual experience (Goulding and Pour Rahimian, 2012).

In the event, as the paper relates, the trial revealed the need for a few small changes but that "The feedback received from the planners suggested that the 4D+VP system effectively tested the feasibility of construction sequencing of mobile tower cranes", which we believe to be an honest and unbiased validation. Only further, larger scale, testing will reveal the ultimate truth of this but, as is normal with R&D work, full implementation of this nature was beyond the scope of the project.

Finally, it is noted that, to date, the prototype tool developed is limited solely to mobile crane movement. There are clearly many opportunities for further development, however, in the provision of applications for heavy plant in general.

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Test	Construction Sequence	Feasibility	Construction Scheduling	Total Duration
1	A	Yes	Generated	120 Days
2	B	Yes	Generated	109 Days
3	C	No	Nil	Nil

Table 1: Results of simulating construction sequences using the VP+4D system

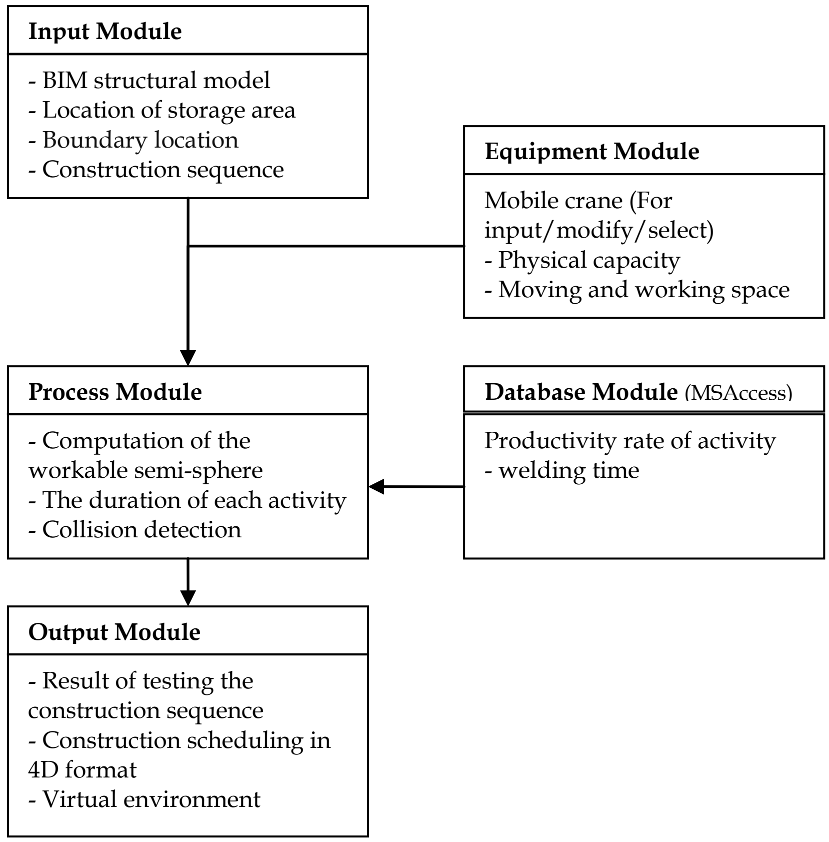
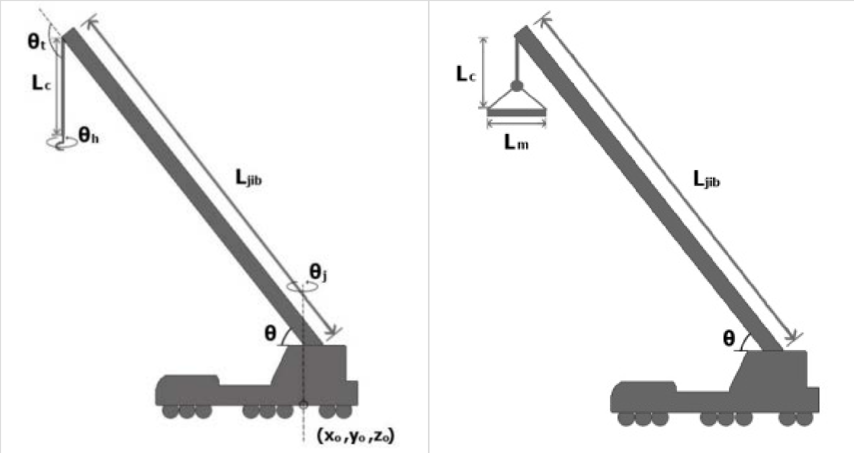


Figure 1. The VP+4D system



(a)	(b)

Figure 2. Illustration of the model of a mobile crane (a) hanging a structural column (b) hanging a structural beam

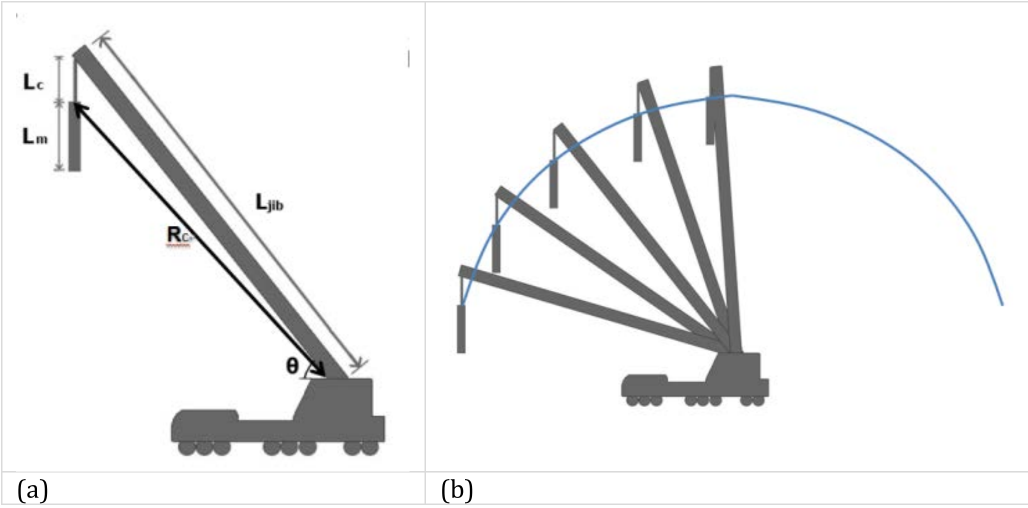
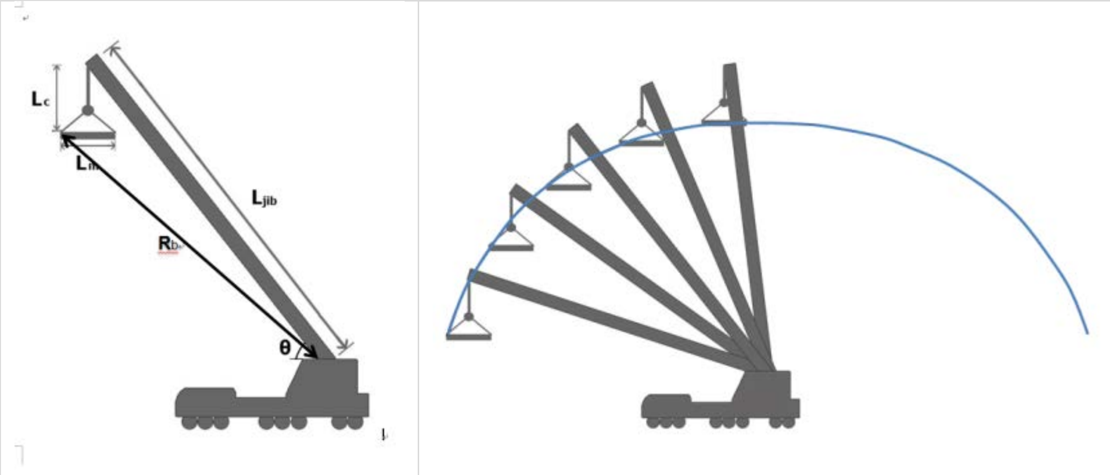


Figure 3. (a) Workable radius when hanging a structural column (b) workable semi-sphere when hanging a structural column



(a) (b)

Figure 4. (a) Workable radius and (b) workable semi-sphere when hanging a structural beam

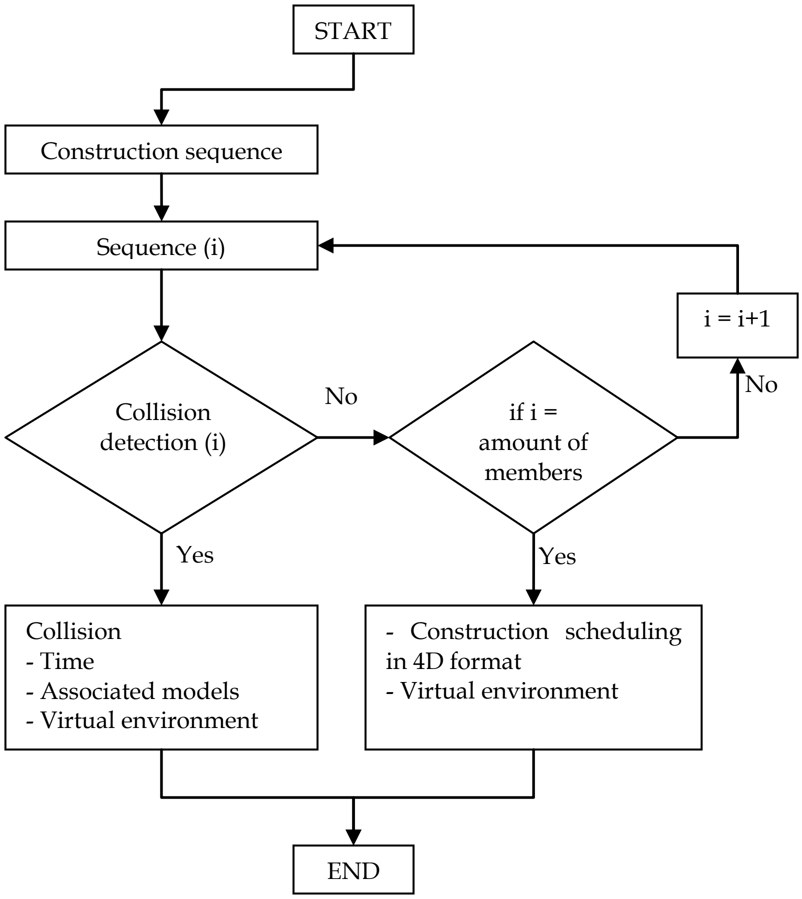
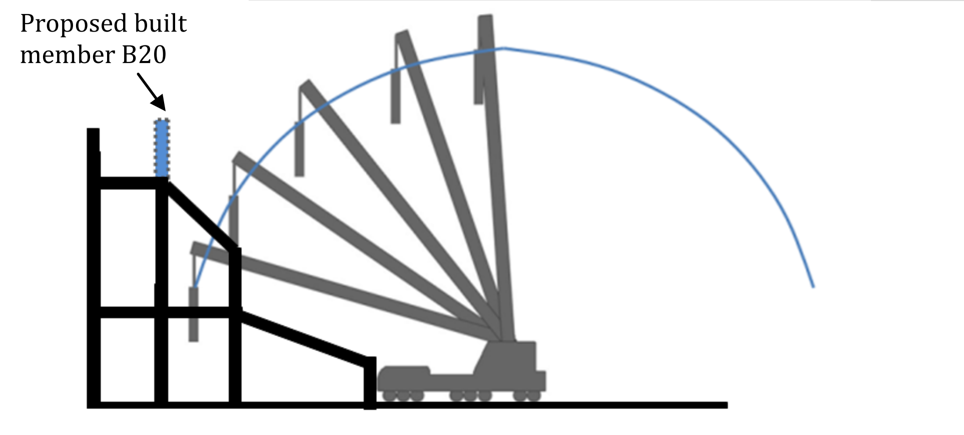
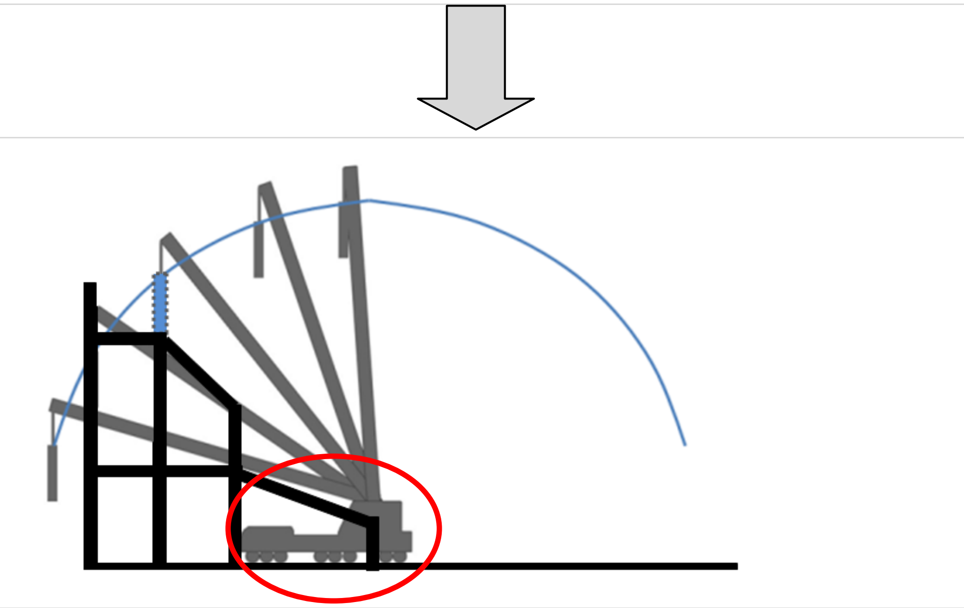


Figure 5. Algorithm for collision detection



(a) The illustration shows that the sphere could not cover the proposed built member due to the obstruction by existing structural members.



(b) If the proposed sequence was followed, a collision would be detected between the crane and existing structural members in the red circled area.

Figure 6. A clash detection situation

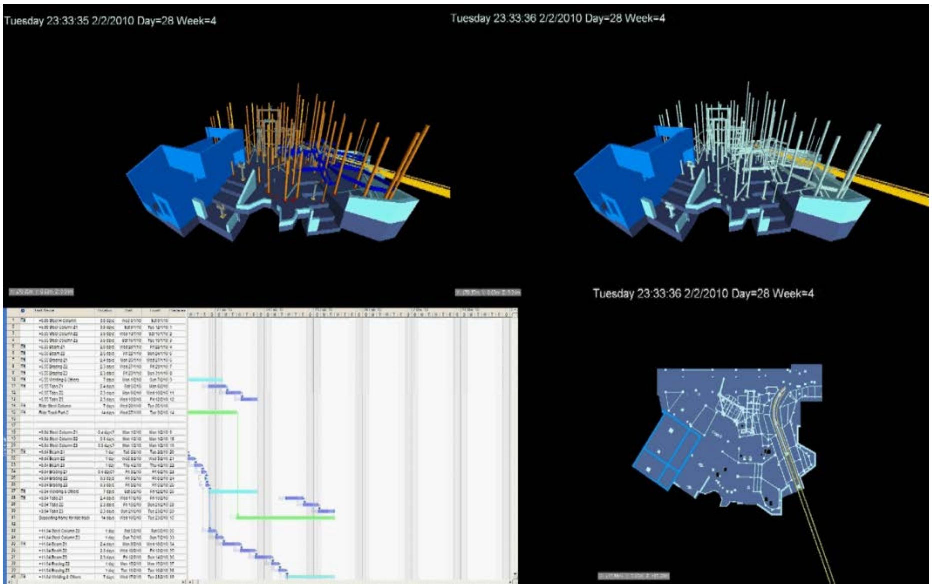


Figure 7. Construction scheduling in 4D format